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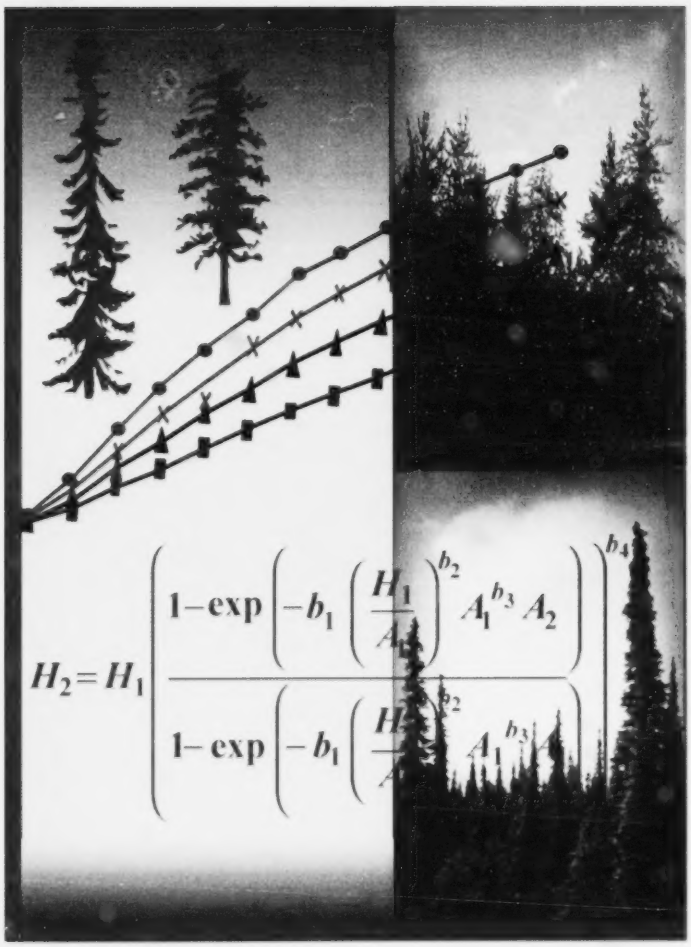
CLIMATE CHANGE RESEARCH REPORT CCRR-15

Responding to Climate Change Through Partnership

An Evaluation of Site Index Models for Young Black Spruce and Jack Pine Plantations in a Changing Climate



Ministry of Natural Resources

Natural. Valued. Protected.

Ontario

Climate Change and MNR: A Program-Level Strategy and Action Plan

The following describes how the Ministry of Natural Resources works to contribute to the Ontario Government's commitment to reduce the rate of global warming and the impacts associated with climate change. The framework contains strategies and sub-strategies organized according to the need to understand climate change, mitigate the impacts of rapid climate change, and help Ontarians adapt to climate change:

Theme 1: Understand Climate Change

Strategy #1: Gather and use knowledge in support of informed decision-making about climate change. Data and information gathering and management programs (e.g., research, inventory, monitoring, and assessment) that advances our knowledge of ecospheric function and related factors and forces such as climate change are critical to informed decision-making. Accordingly, MNR will work to:

- Strategy 1.A: Develop a provincial capability to describe, predict, and assess the important short- (0-5 years), medium- (5-20 years), and long-term (20+ years) impacts of climate change on the province's ecosystems and natural resources.
- Strategy 1.B: Model the carbon cycle.

Strategy #2: Use meaningful spatial and temporal frameworks to manage for climate change. A meaningful spatial and temporal context in which to manage human activity in the ecosphere and address climate change issues requires that MNR continue to define and describe Ontario's ecosystems in-space and time. In addition, MNR will use the administrative and thematic spatial units required to manage climate change issues.

Theme 2: Mitigate the Impacts of Climate Change

Strategy #3: Gather information about natural and cultural heritage values and ensure that this knowledge is used as part of the decision-making process established to manage for climate change impacts. MNR will continue to subscribe to a rational philosophy and corresponding suite of societal values that equip natural resource managers to take effective action in combating global warming and to help Ontarians adapt to the impacts of climate change.

Strategy #4: Use partnership to marshal a coordinated response to climate change. A comprehensive climate change program involves all sectors of society as partners and participants in decision-making processes. The Ministry of Natural Resources will work to ensure that its clients and partners are engaged.

Strategy #5: Ensure corporate culture and function work in support of efforts to combat rapid climate change. Institutional culture and function provide a "place" for natural resource managers to develop and/or sponsor proactive and integrated programs. The Ministry of Natural Resources will continue to provide a "home place" for the people engaged in the management of climate change issues.

Strategy #6: Establish on-site management programs designed to plan ecologically, manage carbon sinks, reduce greenhouse gas emissions, and develop tools and techniques that help mitigate the impacts of rapid climate change. On-site land use planning and management techniques must be designed to protect the ecological and social pieces, patterns, and processes. Accordingly, MNR will work to:

- Strategy 6.A: Plan ecologically.
- Strategy 6.B. Manage carbon sinks.
- Strategy 6.C: Reduce emissions.
- Strategy 6.D: Develop tools and techniques to mitigate the impacts of rapid climate change.

Theme 3: Help Ontarians Adapt

Strategy #7: Think and plan strategically to prepare for natural disasters and develop and implement adaptation strategies. MNR will sponsor strategic thinking and planning to identify, establish, and modify short- and long-term direction on a regular basis. Accordingly, MNR will work to:

- Strategy 7.A: Sponsor strategic management of climate change issues.
- Strategy 7.B: Maintain and enhance an emergency response capability.
- Strategy 7.C: Develop and implement adaptation strategies for water management and wetlands.
- Strategy 7.D: Develop and implement adaptation strategies for human health.
- Strategy 7.E: Develop and implement adaptation strategies for ecosystem health, including biodiversity.
- Strategy 7.F: Develop and implement adaptation strategies for parks and protected areas for natural resource-related recreational opportunities and activities that are pursued outside of parks and protected areas.
- Strategy 7.G: Develop and implement adaptation strategies for forested ecosystems.

Strategy #8: Ensure policy and legislation respond to climate change challenges. Policy, legislation, and regulation guide development and use of the programs needed to combat climate change. MNR will work to ensure that its policies are proactive, balanced and realistic, and responsive to changing societal values and environmental conditions.

Strategy #9: Communicate. Ontarians must understand global warming, climate change, and the known and potential impacts in order to effectively and consistently participate in management programs and decision-making processes. Knowledge dissemination through life-long learning opportunities that are accessible and current is critical to this requirement. MNR will raise public understanding and awareness of climate change through education, extension, and training programs.

An Evaluation of Site Index Models for Young Black Spruce and Jack Pine Plantations in a Changing Climate

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Summary

Assessing potential site productivity is important for forest planning and to predict forest growth and yield. The most common measure of site productivity is site index (SI), defined as the average height of dominant and co-dominant trees (top height) at a specified (index) age. Results from recent studies suggest that height growth of dominant and co-dominant trees can be partially explained by mean annual rainfall and average daily maximum temperature. Ontario summer temperatures are projected to rise by 3 to 6°C by the end of the 21st century, with more pronounced differences in the north. Since these changes are likely to affect tree growth rates, we evaluated the most popular published SI models to determine their suitability to assess climate change effects on the growth of young jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* Mill. BSP).

Nineteen site index (SI) equations, including those commonly applied in Ontario, were evaluated using data from 142 black spruce and 132 jack pine trees collected from 50 plantations (25 per species) from across boreal Ontario. The equations included were base age specific (BAS), base age invariant (BAI), and dynamic. These models were evaluated based on fit statistics and predictive abilities measured by mean bias (observed-predicted), mean absolute bias (MAB), and root mean square error (RMSE).

For BAS SI models, the simplified version of existing natural black spruce and jack pine site index models (the second and third variants of Chapman Richard model for both species and the third and second variants of log logistic models for black spruce and jack pine trees, respectively) were superior to others for predicting heights of dominant or co-dominant trees. For BAI SI models, of the seven models compared three demonstrated superior predictive abilities in terms of bias across site, site quality, and age classes for both species.

Of the dynamic models, the four polymorphic models generated similar predictive accuracy across site, site quality, and age classes for both species. However, only two of them resulted in more consistent estimates for higher productive sites. Biases in height predictions were relatively large, which reduced the utility of the anamorphic SI model. Even though the goodness of fit was acceptable for most of the models assessed, the predictive accuracy of the dynamic models was not as high as expected. This indicates that the local parameter (site specific parameter) used in dynamic models is not adequately robust to explain the variability among sites. Therefore, including edaphic and climatic variables directly in the models could improve model efficacy by helping to explain site specific variability.

Résumé

Évaluation des modèles d'indice de station des jeunes plantations d'épinettes noires et de pins gris dans des conditions de changement climatique

Il est important d'évaluer la productivité potentielle d'une station pour la planification forestière et la prédiction de la croissance et du rendement forestiers. La mesure la plus courante de productivité d'une station est l'indice de station (IS) qui se définit comme la hauteur moyenne des arbres dominants et codominants (hauteur dominante) à un âge (indice) donné. Les résultats d'études récentes suggèrent que la croissance en hauteur des arbres dominants et codominants peut s'expliquer en partie par la moyenne des précipitations annuelles en pluie et la moyenne des températures maximales quotidiennes. On prévoit que la température des étés ontariens augmentera de 3 à 6 °C d'ici la fin du 21e siècle, surtout au nord. Puisque ce changement risque d'avoir une incidence sur le taux de croissance des arbres, nous avons évalué les modèles publiés d'indice de station les plus populaires, en vue de déterminer leur caractère adéquat pour l'évaluation des répercussions du changement climatique sur la croissance des jeunes pins gris (*Pinus banksiana* Lamb.) et des jeunes épinettes noires (*Picea mariana* Mill. BSP).

Nous avons évalué dix-neuf équations d'indice de station (IS), y compris celles appliquées le plus fréquemment en Ontario, à partir des données de 142 épinettes noires et de 132 pins gris recueillies dans 50 plantations (25 par essence) des forêts boréales de l'Ontario. Ces équations étaient fonction de l'âge (EFA), ou sans référence à l'âge (SRA), et dynamiques. Nous avons évalué ces modèles à partir de statistiques d'ajustement et des valeurs de prédiction mesurées à l'aide de l'écart moyen (observé/prédit), de l'écart moyen absolu (EMA), et de l'écart-type.

Dans le cas des modèles d'IS EFA, la version simplifiée des modèles existants d'indice de station pour l'épinette noire et le pin gris (deuxième et troisième variantes du modèle Chapman Richard pour les deux essences, et troisième et deuxième variantes des modèles log-logistique pour les épinettes noires et les pins gris, respectivement) était supérieure aux autres pour la prédiction de la hauteur des arbres dominants et codominants. Dans le cas des modèles d'IS SRA, parmi les sept modèles comparés, trois se sont révélés supérieurs pour la valeur de prédiction au regard des écarts dans la station, de la qualité de la station et de l'indice d'âge pour les deux essences.

Parmi les modèles dynamiques, les quatre modèles polymorphiques ont révélé que les modèles généraient une précision similaire de la valeur de prédiction dans la station. Toutefois, seulement deux d'entre eux donnaient des estimations plus constantes dans le cas des stations très productives. Les écarts dans les prédictions de la hauteur étaient relativement importants, ce qui réduit l'utilité du modèle d'IS par anamorphose. Même si la qualité de l'ajustement était acceptable pour la plupart des modèles évalués, la précision de la prédiction des modèles dynamiques n'était pas aussi bonne qu'on pensait. Cette observation indique que le paramètre local (paramètre particulier à la station) utilisé dans les modèles dynamiques n'est pas suffisamment robuste pour expliquer la variabilité entre les stations. Par conséquent, ajouter les variables édaphiques et climatiques directement aux modèles pourrait améliorer l'efficacité du modèle en contribuant à expliquer la variabilité particulière d'une station.

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Acronyms Used in Report

A	Age of a tree
ADA	Algebraic difference approach
API	All possible combinations of growth intervals
BA	Basal area
BAI	Base age invarient
BAS	Base age specific
DBH	Diameter at breast height
DPI	Dots per inch
GADA	Generalized algebraic difference approach
H	Height of a tree
MAB	Mean absolute bias
MSE	Mean square error
ND	Non-decreasing
NOI	Non-overlapping intervals
RMSE	Root mean square error
SAS	Statistical analysis system (software)
SI	Site index
TSP	Temporary sample plot

Introduction

A critical prerequisite for accurately predicting forest growth and yield is the ability to measure forest site productivity potential (McDill and Amateis 1992). Knowing site productivity potential helps decision makers focus their management efforts on the most productive sites. However, measuring site productivity (commonly referred to as site quality) is a challenging task. Numerous studies have been carried out and many different approaches proposed to assess site quality. Among these measures, the height growth of dominant and co-dominant trees is generally considered the most reliable indicator of site quality because it is thought to be more closely related to site productivity potential than any other measure (Monserud 1984, McDill and Amateis 1992).

Over the last several decades, much effort has gone into developing techniques to quantify site quality. The primary modelling approaches are either empirical- or process-based. While empirical models require only height and age data, process-based models require information about many variables, including topography, climate, and edaphic conditions. Although most of the models developed to measure site quality are simple empirical models, some process-based models are available as well (e.g., Page 1976, Landsberg and Waring 1997, Chen et al. 1998, Ung et al. 2001, McKenney and Pedlar 2003, Hamel et al. 2004, Swenson et al. 2005). These process-based models have used climatic variables. For example, Ung et al. (2001) used degree days (> 5°C), growing season precipitation, growing season cumulative vapour pressure deficit, and aridity index to model for shade tolerant and intolerant boreal species. McKenney and Pedlar (2003) used mean annual temperature, mean maximum temperature of warmest month, mean temperature during driest three consecutive months of the year, and a variety of precipitation records, including the precipitation during the driest month, during the growing season, and total precipitation during the three consecutive wettest months of year to model jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* Mill. BSP).

The most common measure of site quality is site index (SI), defined as the average height of dominant and co-dominant trees (top height) at a specified (index) age (Sharma et al. 2002). Initially, SI curves were developed using guide curves, a technique of describing a two-dimensional relationship using a hand-drawn curve. These curves were presented as graphs or tables without any mathematical form. Using these guide curves, SI models were developed as early as 1926 (Bruce 1926). The data used to develop these SI curves were collected either from stem analysis (Stage 1963, Carmean 1972) or from permanent sample plots (Garcia 1983) from stands of varying ages growing on a variety of site types. These paired height-age values were then plotted on graph paper, and a "guide" curve was drawn to depict the general trend in the data. All other SI curves were then drawn proportional to the guide curve. These curves are generally referred to as anamorphic because they all have the same shape.

Using the guide curve method, SI curves for jack pine and black spruce were first developed by Gevorkiantz (1956, 1957) and Plonski (1956, 1960), for the U.S. Great Lake states and northern Ontario, respectively. Since all anamorphic SI curves are proportional to the guide curve, if the guide curve is biased then the entire family of anamorphic curves will be biased. Another weakness of anamorphic SI curves is the inherent assumption of a common shape for all site classes. For many species, the shape of the height curve varies with site quality.

Families of SI curves with differing shapes for different SI classes are referred to as polymorphic. These polymorphic SI models have been formulated using a variety of approaches. Early SI models were fitted as base age specific (BAS) (e.g., Carmean 1972; Payandeh 1974a,b; Newnham 1988). In this case, the

base age is fixed before the model is constructed and the model parameters are hypothesized as a function of height at base age (Clutter et al. 1983). Therefore, these models are static in nature and estimate the top height at a particular index age. However, they require two separate equations: one for the height-age relationship and another for SI.

Two main problems occur with base age specific SI models: First, if the equations are complex, they are difficult to reformulate for SI. Second, even if the equation is solved for SI, it produces different values of SI for different height-age information from the same data set because different sum of squares are minimized in fitting the regressions (Krumland and Eng 2005). In other words, changing the base age can result in different SI values for the same site (Heger 1973). Another concern is the measurement error associated with SI because when it occurs in the response variable (right hand side of the equation), it violates the modelling assumption (Goelz and Burk 1992, Krumland and Eng 2005).

To eliminate the problem related to base age selection, Bailey and Clutter (1974) introduced the concept of base age invariance (BAI). These models are path invariant because the parameters are estimated using an algebraic difference approach (ADA), hence are dynamic. As a result, the final height prediction is independent of the initial selected age. Since then, numerous BAI SI models have been developed (e.g., Bailey and Clutter 1974, Goelz and Burk 1992, McDill and Amateis 1992, Newton 1992).

Cieszewski and Bailey (2000) further expanded parameter estimation techniques of BAI SI models by developing the generalized algebraic difference approach (GADA). In this approach, local (specific to stand or site) and global (across stand or site) parameters are estimated simultaneously. These models do not refer to index age height (Cieszewski and Bailey 2000). A number of studies (e.g., Cieszewski 2002, 2003; Krumland and Eng 2005; Cieszewski et al. 2006; Dieguez-Aranda et al. 2006; Nord-Larsen 2006; Cieszewski and Strub 2008) have adopted this approach in developing SI equations. In addition, some researchers (e.g., Wang et al. 2007, Wang et al. 2008a) have explored the use of a mixed-effects modelling approach to develop SI equations.

Wang et al. (2007) reported that including mean annual rainfall and average daily maximum temperature as additional explanatory variables in their model greatly improved the fit statistics of SI models. Ontario summer temperatures could potentially rise by 3 to 6°C by the end of the 21st century, with more pronounced differences in the north (Colombo et al. 2007). These changes will likely significantly affect current growth rates.

The objectives of this study were to fit and evaluate a number of SI models for possible climate change effects using data from plantation-grown jack pine and black spruce trees from boreal Ontario. Specifically we used:

- SI models developed and used in Ontario
- Other recently developed models that use different methods and modelling approaches

A Description of Site Index Models and Rationale for Testing Them

Site index models developed for Ontario species are summarized in Table 1. Most of these were developed using the BAS and BAI approaches as mixed-effects SI models have not yet been introduced to Ontario. The exact model forms displayed in Table 1 could not be fitted for the trees used in this study because they were over-parameterized (had more parameters than necessary). Therefore, we included variants of most of these models along with other recently published equations in our comparison. The models examined were:

Base Age Specific (BAS) Site Index Models[1]

Newnham model (Newnham 1988)

$$H = b_1 S^{b2}\left(1 - k^{(A/A_1)}\right)^{b_4 S^{b5}} \quad (1)$$

where H = height at age A, $k = 1 - \left(S / b_1 S^{b_2}\right)^{1/b_4 S^{b5}}$, S = site index (height at index age A_1) and b_1-b_5 are model parameters.

Variant 1 of Chapman-Richards model (Chapman et al. 1923, Richards 1959)

$$H = aS^b\left(1 - exp(-cA)\right)^d \quad (2)$$

Variant 2 of Chapman-Richards model (Krumland and Eng 2005)

$$H = aS^b\left(1 - exp(-cA)\right)^{(d+e/S)} \quad (3)$$

Variant 3 of Chapman-Richards model (Payandeh 1974b)

$$H = a_1 S^{a_2}\left(1 - exp(bA)\right)^{c_1 + c_2 S} \quad (4)$$

Variant 1 of log-logistic model (Krumland and Eng 2005)

$$H = \frac{(b_1 + S)}{(1 + b_2 / S)exp(b_3 ln(A))} \quad (5)$$

[1] Note: In the equations in this report, *a, b, c, d, e,* etc. (with or without subscripts) refer to model parameters and *S* is used to denote SI.

***Table 1**. Existing site index models for jack pine and black spruce in Ontario (H= height, S = site index; a, b are parameters; A = age).*

Species	Model Description and Name		Source
Black spruce, jack pine, and others	Guide curves developed using graphical methods. No equations were developed for these curves		Plonski 1956, 1960
Black spruce and jack pine	$H = a_0 + a_1 S$ and $S = b_0 + b_1 H$	(i)	Heger 1968
Black spruce, jack pine, and others	$H = b_1 S^{b2}\left(1 - e^{b_3 A}\right)^{b_4 S^{b5}}$	(ii)	Payandeh 1974a
White spruce	$H = b_1 S^{b2}\left(1 - k^{(A/A_1)}\right)^{b_4 S^{b5}}$ where, $k = 1 - \left(S / b_1 S^{b_2}\right)^{1\ b_4 S^{b5}}$	(iii)	Newnham 1988
Jack pine in north central Ontario	$H = 1.3 + b_1 S^{b2}\left(1 - e^{b_3 A}\right)^{b_4 S^{-b5}}$	(iv)	Carmean and Lenthall 1989
Jack pine in north central Ontario	$H_2 = 1.3 + (H_1 - 1.3)\left(\frac{1 - \exp\left(-b_1\left(\frac{H_1}{A_1}\right)^{b_2} A_1^{b_3} A_2\right)}{1 - \exp\left(-b_1\left(\frac{H_1}{A_1}\right)^{b_2} A_1^{b_3} A_1\right)}\right)^{b_4}$	(v)	Goelz and Burk 1992
Black spruce, jack pine, and others	$H = b_1 S^{b2}\left(1 - e^{b_3 A}\right)^{f(b_1, b_2, b_3, t_i, S)}$, where $f(b_1, b_2, b_3, t_i, S) = \ln\left(S^{1-b_1}\right) / \ln\left(1 - e^{b_3 t_i}\right)$	(vi)	Payandeh and Wang 1994a
White spruce	$H_2 = b_1 H_1^{b2}\left(1 - e^{-b_3 A_2}\right)^{c}$, where $c = \ln\left(\frac{H_1}{b_1 H_1^{b_2}}\right) / \ln(1 - e^{-b_3 A_1})$	(vii)	Payandeh and Wang 1994b
Black spruce, white spruce, and jack pine	(ii), (v), (vi), (vii)		Payandeh and Wang 1995
Jack pine	$H = 1.3 + b_1 (S - 1.3)^{b2}\left(1 - k^{(b_3 A/50)}\right)^{(S-1.3)^{b4}}$ where, $k = 1 - \left(\frac{S - 1.3}{b_1 (S - 1.3)^{b2}}\right)^{\frac{1}{b_3 (S - 1.3)^{b4}}}$	(viii)	Carmean et al. 2001
Black spruce and trembling aspen	$H = 1.3 + b_1 (S - 1.3)^{b2}\left(1 - k^{(A/50)}\right)^{b_3 (S-1.3)^{b4}}$, where $k = 1 - \left(\frac{S - 1.3}{b_1 (S - 1.3)^{b2}}\right)^{\frac{1}{b_3 (S-1.3)^{b4}}}$	(ix)	Carmean et al. 2006

Variant 2 of log-logistic model (Wang et al. 2008a)

$$H = \frac{a_1 S^{a_2}}{\left(1 + b_1 S^{-b_2} A^{-c}\right)} \tag{6}$$

Variant 3 of log-logistic model (Wang et al. 2008a)

$$H = \frac{a_1 S^{a_2}}{\left(1 + b_1 A^{-c_1 S^{c_2}}\right)} \tag{7}$$

These models were chosen for evaluation for the following reasons: Equation (1) is flexible, expresses polymorphic height-growth patterns, and is constrained to pass through tree height at index age (Newnham 1988, Carmean et al. 2001). According to Carmean et al. (2006), Equation (1) was the most precise model for computing SI for young plantations. Equation (2) has been shown to fit most Canadian crop tree species (Payandeh 1974a, b). Equations (3) and (4) are modified forms of the equation used by Carmean and Lenthall (1989) and Carmean et al. (2001), and were used because the original model was over-parameterized for the data set used in this study. Krumland and Eng (2005) used Equation (3) for a number of conifer species and found it predicted tree heights better than Equation (2). Similarly, Equation (5) was included because previous studies (Cieszewski 2003, Krumland and Eng 2005, Wang et al. 2008a) reported that it provided better predictions for their data sets than other models. Krumland and Eng (2005) also reported that this model could be used to extrapolate beyond the range of the available data with reasonable results. Equations (6) and (7) are logistic models that have been used in a number of studies (e.g., Nigh 2001, 2004; Wang et al. 2008a).

Base Age Invariant (BAI) Site Index Models

The following BAI models were evaluated:

Goelz and Burk (1992)

$$H_2 = H_1 \left(\frac{1 - \exp\left(-b_1 \left(\frac{H_1}{A_1} \right)^{b_2} A_1^{b_3} A_2 \right)}{1 - \exp\left(-b_1 \left(\frac{H_1}{A_1} \right)^{b_2} A_1^{b_3} A_1 \right)} \right)^{b_4} \tag{8}$$

where, H_1 = height at age A_1, H_2 = height at age A_2 (A_2 could be greater or less than A_1).

A difference form of Chapman-Richards model (Richards 1959)

$$H_2 = H_1 \left(\frac{1 - \exp(-b_1 A_2)}{1 - \exp(-b_1 A_1)} \right)^{b_2} \tag{9}$$

Modified difference form of Chapman-Richards model (Dieguez-Aranda et al. 2006)

$$H_2 = a\left(1-\left(1-(H_1/a)^{1/c}\right)^{A_2/A_1}\right)^c \quad (10)$$

McDill and Amaeteis (1992)

$$H_2 = \frac{b_1}{\left(1-(1-b_1/H_1)(A_1/A_2)^{b_2}\right)} \quad (11)$$

Bailey and Clutter (1974)

$$H_2 = \exp\left(a+(\ln(H_1)-a)(A_2/A_1)^b\right) \quad (12)$$

Amateis and Burkhart (1985)

$$H_2 = exp\left(ln(H_1)(A_1/A_2)^b\, exp(a(1/A_2-1/A_1))\right) \quad (13)$$

Clutter and Lenhart (1968)

$$H_2 = \exp\left((a+b/A_2+(\ln(H_1)-a-b/A_1)\right)\exp\left(c(1/A_2-1/A_1)\right)) \quad (14)$$

These were chosen for evaluation because: Goelz and Burk (1992) recommended Equation (8) for jack pine in north central Ontario. Equation (9) is simple in model form and has been used in many studies (e.g., Lundgren and Dolid 1970, Carmean 1972). The parameters of equations (10) and (11) can be biologically interpreted (McDill and Amateis 1992) and equations (12) – (14) have been widely used (e.g., Cao 1993, Huang 1997, Calama et al. 2003).

Generalized Algebraic Difference Approach (GADA)-Based Dynamic Site Index Models

Even though BAI models are path invariant, they do not include parameters that capture site productivity values. Cieszewski and Bailey (2000) advanced SI estimation techniques by introducing the GADA method to generate a site-specific value for site productivity. These models have become very popular in other regions of North America (e.g., Krumland and Eng 2005) but have not been introduced to Ontario. A series of steps are needed to develop these equations:

1. Select a suitable base equation that expresses height growth as a function of age.
2. Identify the parameters in the base equation that potentially change with different levels of site productivity and replace them as a function of X (a local parameter).
3. Solve the resulting model in step (2) for X in terms of initial conditions of height and age (H_0 and A_0) and produce final GADA-based dynamic SI model (Krumland and Eng 2005).

We evaluated five GADA-based dynamic SI models recommended by Krumland and Eng (2005):

Model developed by assuming the asymptote in the Chapman-Richards model as site-specific parameter

$$H=H_0\left(\frac{1-exp(b_1A)}{1-exp(b_1A_0}\right)^{b_2} \quad (15)$$

where, H_0 and A_0 are initial height and age, respectively, representing initial conditions for a particular site and other notations are as previously defined.

Model developed by assuming the asymptote and shape parameter in the Chapman-Richards model as site-specific parameters

$$H=H_0\left(\frac{1-exp(b_1A)}{1-exp(b_1A_0}\right)^{(b_2+b3/R_0)} \quad (16)$$

where $R_0=\frac{(ln(H_0)-b_2Y)\pm\sqrt{(ln(H_0)-b_2Y)^2-4b_3Y}}{2}$, and $Y=ln(1-exp(b_1A_0))$.

Schumacher (1939) model

$$H=exp\left(ln(H_0)-b_1A_0^{b_2}+b_1A^{b_2}\right) \quad (17)$$

King and Pardon model (Krumland and Eng 2005)

$$H=\frac{A^{b_1}}{b_2+b_3R_0+R_0A^{b_1}} \quad (18)$$

where $R_0=\frac{\frac{A_0^{b_1}}{H_0}-b_2}{\left(b_3+A_0^{b_1}\right)}$

Model developed with log-logistic equation as base function

$$H=\frac{b_1+R_0}{1+(b_2/R_0)exp(b_3\,ln(A))} \quad (19)$$

where $R_0=\frac{(H_0-b_1)+\sqrt{(H_0-b_1)^2+4b_2(\exp(b_3)\ln(A_0))H_0}}{2}$

These were chosen because equations (15) – (19) were the recommended SI models for young growth forest in northern California by Kurmland and Eng (2005). In addition, equations (15) – (16) are the most widely used SI model forms in various studies (e.g., Dieguez-Aranda et al. 2005, 2006; Wang et al. 2007, 2008a, b), and equation (17) was used by Strub and Cieszewski (2006). Except for equation (15), all of these are polymorphic SI models.

Methods

All height, SI, and age measurements were based on breast height. As an example, a SI of 7 m means that the top height at index age 20 ranged between 6.5 m and 7.5 m above breast height at that site. Tree height growth prior to reaching breast height is erratic and determined by factors other than site quality (Carmean 1975, Carmean and Lenthall 1989, Goelz and Burk 1992), thus height growth below breast height age was not included in this study.

Data

The data used in this study were collected from plantation-grown jack pine and black spruce trees. For both species, 25 even-aged monospecific plantations from throughout the boreal forest region (Rowe 1972) of northern Ontario were sampled. Within each plantation, three variable-size circular temporary sample plots (TSPs) were established. The minimum plot size was set at 400 m^2 but was increased if necessary to include a minimum of 80 trees of the target species.

Diameter at breast height (1.3 m) and height measurements were collected for all live trees in the sample plot, regardless of species, using Ontario's growth and yield standards (Hayden et al. 1995). All samples were sequentially numbered and the cumulative basal area was determined for each species. The total cumulative basal area of target species trees was divided into five BA classes. From each basal area class, three planted trees that did not exhibit any visible deformities, such as forks, major stem injuries, dead or broken tops, were randomly selected for destructive sampling. Thus, a minimum of 15 trees (3 trees per 5 basal area classes) were sampled from each plot. Of the 15 trees in each TSP, three dominant or co-dominant trees were selected for analysis. That resulted in nine trees from each site for analysis.

From each sampled tree, disks were cut at 0.15, 0.5, 0.9, and 1.3 m (breast height) from ground level. The remaining height of the tree was then divided based on one of two sampling schemes: 5% and 10% of relative height. For the 5% sampling scheme, the remaining height was divided by 20 and the disks were cut at that interval from breast height; similarly, for the 10% sampling scheme, the remaining height was divided by 10 and the disks were cut at the resulting interval. At each site, the 5% sampling scheme was applied to 20% of sample trees and the remainder were cut using the 10% scheme. This resulted in 23 disks and 13 disks per tree for the 5% and 10% sampling schemes, respectively.

Each sampled tree and disk was assigned a unique code. All disks from a tree were placed in a large breathable bag, transported, and stored at –10°C until 24 hours prior to preparation for analysis, which involved sanding the surface of the disk. At time of analysis, geometric mean radius was calculated from the diameters obtained from the major (r_1) and minor (r_2) axes on each disk (i.e., $r = (r_1.r_2)^{0.5}$). On each section, two radii matching this geometric mean radius were located and marked. All measurements were to the inner bark. The sanded sections were scanned and the resulting images were saved at a resolution of 720 DPI or higher. These images were then analyzed for diameter growth and ring number along the marked radii from the pith using WINDENDRO™ software.

Subedi and Sharma (in review) found Graves's method (1906) to be more accurate than other available methods in locating the ends of annual height growths for the trees included in this study. Therefore, this method was used to determine the ends of annual height growth along the bole using the height of the disk and number of rings in the disks. For each tree, observed heights and ages were plotted to form height-age curves. These curves were closely inspected for indications of early suppression in height growth, top breakage, or dieback. Trees with injuries or signs of early suppression were discarded. One hundred and ninety six jack pine and 211 black spruce trees were eligible for analysis from 23 and 22 sites,

respectively. From each site, trees from two of the three sample TSPs (randomly selected) were used for model calibration (model calibration data set) and the rest (trees from one TSP) were reserved for evaluation (validation data set). Summary statistics for tree and stand characteristics are presented in Table 2. The growth interval required to fit BAI models was set to five years. As recommended by Huang (1997), BAI models were fitted using all possible growth interval combinations. The PROC MODEL procedure in SAS was used to fit the models.

Table 2. *Summary statistics for breast height diameter (DBH), total height, breast height age, and site index (SI) (base age 20) for northern Ontario plantation black spruce and jack pine trees used in this study.*

Species/Variable	Calibration					Validation				
	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
Black spruce										
DBH (cm)	142	16.38	2.79	10.30	24.80	69	16.32	2.99	10.10	23.50
Height (m)	142	12.55	2.21	7.28	17.85	69	12.67	2.32	7.94	16.82
Breast height age (yr)	142	31.87	6.97	20.00	44.00	69	31.72	7.38	20.00	46.00
SI (m)	142	7.53	1.10	4.75	9.48	69	7.61	1.13	5.01	10.03
Jack pine										
DBH (cm)	132	19.69	3.84	12.30	30.40	64	19.93	4.36	12.90	34.30
Height (m)	132	16.69	2.02	11.80	21.28	64	16.57	2.10	11.82	20.88
Breast height age (yr)	132	37.95	9.25	24.00	60.00	64	37.53	8.93	23.00	59.00
SI (m)	132	9.61	1.31	5.87	13.05	64	9.66	1.27	7.19	12.53

Model Comparison

Once height growth/SI models were fitted using the calibration data set, the validation data set was used to evaluate the models based on the following criteria:

- Goodness of fit. For each SI model the mean square error (MSE), adjusted R^2, and significance level of model parameters were calculated.
- Height prediction precision. For the validation data set, models were used to estimate tree heights. Mean and mean absolute bias (observed – predicted) in predicting heights along with their root mean standard error across the site, age, and SI classes were calculated for each model as:

$$\text{Mean bias (Bias)} = \frac{\sum\left(H_{obs} - \hat{H}\right)}{n}$$

$$\text{Mean absolute bias (MAB)} = \frac{\sum abs\left(H_{obs} - \hat{H}\right)}{n}$$

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{\sum\left(H_{obs} - \hat{H}\right)^2}{n-1}}$$

where, H_{obs} and $\hat{H}$ are observed and predicted heights, respectively, for a model and n is the total number of observations available for evaluation.

Results and Discussion

Base Age Specific (BAS) Site Index Models

All BAS models (equations (1) – (7)) fitted height growth of the dominant and co-dominant trees adequately for both species. The models demonstrated coefficients of determination (R^2) of at least 98.17% and 97.95% for black spruce and jack pine, respectively. All parameters were significantly different from zero ($p < 0.05$) except a_2 for equation (6) for jack pine.

These models were further analyzed using the validation data set. The predictive abilities of these models were evaluated across site, age, and SI classes (base age 20) by calculating bias (observed-predicted), mean absolute bias (MAB), and root mean square error (RMSE) of predicted heights of dominant and co-dominant black spruce and jack pine trees. Mean bias, MAB, and RMSE resulting from these models were similar across sites for both species. However, for one site for each species the mean bias was larger than the other sites for all models.

Mean bias across SI classes was slightly larger for equation (5) for poor (SI=5) and for equation (2) for better (SI=9) sites with black spruce. Similarly, the bias was slightly larger for equation (5) for poor (SI=8) and for equations (2) and (7) for better (SI=12) sites with jack pine. With respect to bias across age classes, equation (5) resulted in relatively smaller bias for older trees and slightly larger bias for younger trees. Similar trends were found for MAB and RMSE for both species.

Base Age Invariant (BAI) Site Index Models

Base age invariant (BAI) models are constructed using different combinations of height growth intervals. Given that data structure plays an important role in fitting BAI SI models, three data structures were evaluated in this study: (1) all possible combinations of 5-year growth intervals (API) ($H_2 > H_1$ and $H_1 > H_2$ for both scenarios), (2) all possible combinations of non-decreasing growth intervals (NDI), and (3) non-overlapping growth intervals (NOI). Details about these structures are described by Huang (1997). Similar to results reported by Huang (1997), Goelz and Burk (1992), and Cao (1993), for the data sets used in this study the API structure demonstrated a better fit than other structures. Therefore, all BAI models (equations (8) – (14)) were fitted using the API structure for both species.

All BAI SI models fitted the model calibration data well. Heights of the dominant trees predicted using most of the BAI SI models (equations (8) – (14)) were very close to their observed counter parts for both black spruce and jack pine trees. Equation (13) performed the poorest in predicting the height of trees as it generated a larger mean bias across the sites, SI, and age classes for both species. For example, the mean bias in height prediction for validation data across sites ranged from -0.20 m to 0.89 m and -1.23 m to 1.14 m for black spruce and jack pine, respectively. Among other models, equations (8) and (9) produced slightly larger bias across sites. The MAB and RMSE followed the same trend of mean bias across site, SI, and age classes for all models for both species.

The ability to accurately predict height of dominant and co-dominant trees increased from BAS to BAI models across sites, SI, and age classes. BAI SI models are path invariant as these models may predict height at any age given height at other age. In addition, these models can predict SI given the measured height and age, as well as height, given the SI and age. The path invariance is one of the desired properties of a well-suited SI equation (Goelz and Burk 1992).

Generalized Algebraic Difference Approach (GADA)-Based Dynamic Site Index Models

GADA-based dynamic SI equations (15) – (19) were fitted to both black spruce and jack pine 5-year growth interval data. Unlike BAS and BAI, these models contain parameters specific to the site (local parameters). The coefficient of determination (R^2) was greater than 98.1% for black spruce and 97.8% for jack pine. Mean bias, MAB, and RMSE in predicting heights of trees for the validation data set were also calculated for these models by site, SI, and age classes. All but equation (15) predicted heights of black spruce accurately with an acceptable range of mean bias, MAB and RMSE across the sites, site index, and age classes. The same was true for jack pine, however, the magnitude of these statistics were slightly higher than for black spruce.

Equations (16) – (19), which provided better height growth predictions than equation (15), were further evaluated by generating SI curves across a range of SI (Figures 1 and 2) for both species. Parameter estimates used in generating these curves are presented in Table 3. All four models produced similar height curves for poor to medium productivity sites for both species. However, equations (18) and (19) resulted in more realistic height estimates for higher productivity sites than equations (16) and (17).

Since the trees used in this study were very young (mean age <40 yrs), we were unable to compare our models with those published for natural stands. For example, Plonski (1974) SI curves start at age 20, whereas our base age for SI was 20 yrs.

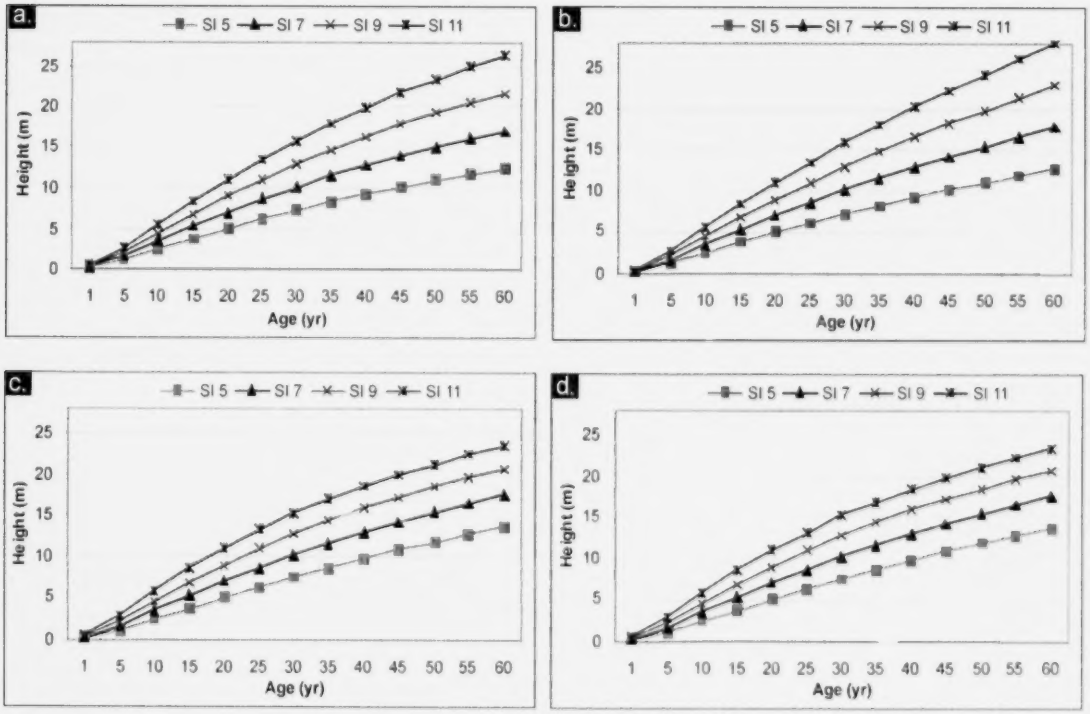

Figure 1. *Generalized algebraic difference approach (GADA)-based dynamic site index curve generated using (a) Chapman Richard (Eq. 16), (b) Schumacher (Eq. 17), (c) King and Pardon (Eq. 18), and (d) log-logistic (Eq. 19) models for northern Ontario plantation black spruce trees.*

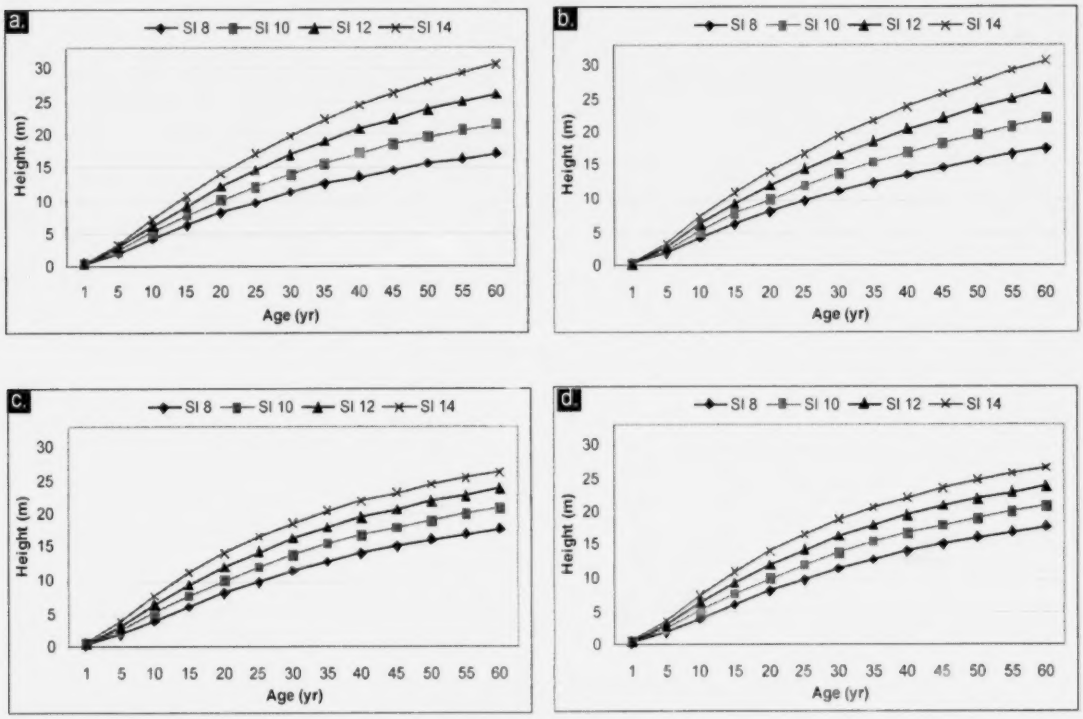

Figure 2. *Generalized algebraic difference approach (GADA)-based dynamic site index curve generated using (a) Chapman Richard (Eq. 16), (b) Schumacher (Eq. 17), (c) King and Pardon (Eq. 18), and (d) log-logistic (Eq. 19) models for northern Ontario plantation jack pine trees.*

Table 3. *Parameter estimates (standard errors in parentheses) for GADA-based dynamic site index models (Equations (16)-(19))** generated using stem analysis data collected from jack pine and black spruce plantations in northern Ontario.*

	Black spruce			Jack pine		
Equation	**b1**	**b2**	**b3**	**b1**	**b2**	**b3**
Eq. 16	-0.0188 (0.002)	0.9869 (0.1699)	0.5537* (0.5713)	-0.02765 (0.0015)	1.4553 (0.1267)	-0.90225 (0.4166)
Eq. 17	-9.0390 (0.5238)	-0.1733 (0.0202)		-6.90976 (0.0552)	-0.30817 (0.018)	
Eq. 18	1.1601 (0.0235)	-3440607* (282201)	142930000 (0.001)	1.235107 (0.0229)	-7.2718* (4.3727)	339.2658 (142)
Eq. 19	43.2797 (10.244)	-218.2270 (1192.6)	-1.1588 (0.0245)	18.31365 (8.3428)	1453.793* (855)	-1.23387 (0.0229)

** See text for equation details
* Not significant at alpha=0.05

Conclusions

A variety of site index (SI) equations, including those commonly used in Ontario, were fitted and evaluated using data from plantation grown jack pine and black spruce trees from Ontario's boreal forest. The equations included were base age specific (BAS) (equations (1) – (7)), base age invariant (BAI) (equations (8) – (14)), and GADA-based dynamic (equations (15) – (19)). Based on fit statistics and predictive abilities measured by mean bias (observed-predicted), MAB, and RMSE, we conclude that:

1. Among BAS SI models, equations (3), (4), and (7) more accurately predicted black spruce height and equations (3), (4), and (6) best predicted jack pine height.
2. Among BAI SI models, equations (10) – (12) provided more accurate predictions (in terms of bias) across site, site quality, and age classes.
3. In terms of predictive accuracy, BAI models were better than BAS models.
4. GADA-based dynamic models (16) – (19) provided similar predictive accuracy across sites, site quality levels, and age classes. However, for trees from sites with higher site productivity, equations (18) and (19) provided better height predictions than equations (16) and (17). Poor results from equation (15) preclude it from use to estimate tree heights.
5. Despite reasonable goodness of fit, the predictive accuracy of GADA-based dynamic models was lower than expected. This indicates that the local (site-specific) parameter used in these models is not adequately robust to explain the variability among sites. Including edaphic and climatic variables directly in the models could improve their efficacy by accounting for variability attributable to changes in climate.

Recommendations

1. GADA-based dynamic models (18) – (19) are more accurate than other BAS and BAI models for predicting the height of dominant and co-dominant plantation grown jack pine and black spruce trees. Therefore, these equations can be used in estimating stand height and should be considered for use in Ontario.
2. Wang et al. (2007) reported that including mean annual rainfall and average daily maximum temperature as additional explanatory variables in their model greatly improved the fit statistics of SI models. Ontario summer temperatures are projected to rise by 3 to 6°C by the end of the 21st century, with more pronounced differences in the north. These changes will likely significantly affect current growth rates. Therefore, climate indices should be incorporated in future SI curves.
3. To increase the prediction accuracy of SI models, the effects of other site specific variables (such as topography and edaphic conditions including soil nutrients) should also be considered.

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